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A METHOD OF MEASURING MEAN TEMPERATURES IN THE FIELD

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A recent report on current avalanche research in Europe (1) has described and illustrated a chemical method of measuring mean temperatures over long periods in the field. At the time that report was prepared, complete technical details were not available. This information has recently been received from Switzerland, and the present Miscellaneous Report has been prepared to disseminate details to research foresters who may find the method useful.

Many aspects of microclimate (avalanche control, reforestation, timberline ecology, fire conditions) can be studied to best advantage if mean air and soil temperatures are available for many different sites in a given locality. Ordinary methods of instrumentation for collecting mean temperature data, such as thermographs or recording thermometers, are complex and costly when used for simultaneous measurements at many different sites. The chemical method described below utilizes a small, simple and inexpensive sensing element which permits widespread temperature observations with minimum cost and effort. This method, based on the temperature-dependency of sugar inversion, was first introduced some 20 years ago, but information on it apparently has not received wide distribution. At present the method is being used in the comprehensive study of avalanche prevention, reforestation and timberline ecology being carried out by agencies of the Swiss government on the Stillberg Project near Davos, Switzerland.

Fundamentals of the method and its field application are discussed in a paper by Pallman and Frei, (2) published in 1943. The pertinent sections of this paper are translated and presented below.

A New Principle and Method of Temperature Measurement

Until now there have been several proven methods available for temperature measurement:

a) Isolated temperature measurements with a thermometer, thermoelement, or electrical resistance thermometer.

b) Continuous temperature measurement with a thermograph or recording apparatus for thermo-elements.

c) Measurement of mean temperature values for short intervals (hours and days) by the electrolytic method of E. Tamm. (3)

Isolated temperature values have only limited value for the soil scientist or ecologist. The simultaneious observation of many individual temperatures is either time-consuming or requires a large number of assistants. Automatic temperature recording apparatus is expensive and requires careful maintenance.

In recent years a new method of measuring mean temperatures has been evolved (4) which is based on chemical principles, and has been given practical field tests during the years 1939 to 1941. It has been demonstrated to be inexpensive, reliable and effective. The temperature sensitive elements hung in the air or buried in the ground consist of small glass ampoules filled with a sterile, buffered sugar solution. Since they have proven to be completely unaffected by the ravages of a mountain climate, they require no maintenance. The effective mean temperature (eT-value) can be measured over days, weeks or months.

<u>a) The chemico-physical basis of the method</u>

Cane sugar (saccharose, sucrose) dissolved in water is converted into dextrose and fructose by the action of hydrogen ions. The cane sugar is <u>inverted.</u>

In a constant concentration of hydrogen ions (buffered solution), this inversion is strongly accelerated by <u>rising temperatures</u>. If one knows the functional relationship between inversion rate and temperature, the mean

temperature for a given observation interval can be determined from the amount of cane sugar inverted, either graphically (fig. 1) or by calculation.

The inversion rate dx/dt , with constant temperature and within a limited variation of pH value in the buffered solution, obeys the following expression:

$$\frac{dx}{dt} = K.\ H.\ (A - x) \qquad \text{Eq. 1}$$

where

A = initial cane sugar concentration at time t = 0

x = invert sugar formed after time t

A-x = cane sugar remaining after time t

t = time, in this research expressed in days

H = hydrogen ion concentration

K = inversion constant for the temperature T

The inversion constant K can be calculated for a given constant temperature T by integration of Equation 1:

$$K = \frac{1}{H.t} \log \left[\frac{A}{A - x}\right] \qquad \text{Eq. 2}$$

The experimental determination of the inversion constant K follows quickly and simply from optical polarization For the optical polarization measurement of the course of the inversion, Equation 2 can be rewritten:

$$K = \frac{1}{H.t} \log \frac{\alpha_0 - \beta_0}{\alpha - \beta_0} \qquad \text{Eq. 3}$$

where

α_0 = optical rotation angle of the cane sugar solution at $t = 0$

β_0 = optical rotation angle of invert sugar at $t = \infty$

α = optical rotation angle of the partially inverted solution after t days.

The inversion constant K was experimentally determined in the Institute of Agricultural Chemistry for many fixed temperatures between -0.3° C and 37 7° C.

Table 1

Mean Temperature of the Various Thermostats and Mean Values of the Corresponding Corresponding Inversion Constant K_T

(Buffered Sugar solutions of pH=2.50 and 2.90)

Mean Thermostat Temperature	Mean Error of Thermostat Temp.*	Mean Value of Observed Inversion Constant	Mean Error of the Mean Constant
-0.3° C	±0.05° C	0.0548	±0.0021
+5.4° C	±0.05° C	0.1461	±0.0027
9.0° C	±0.08° C	0.2682	±0.0020
12.5° C	±0.09° C	0.5195	±0.0051
15.2° C	±0.14° C	0.7485	±0.0064
18.3° C	±0.05° C	1.2876	±0.0117
21.3° C	±0.08° C	2.0930	±0.0082
24.4° C	±0.06° C	3.3338	±0.0081
27.3° C	±0.11° C	5.3021	±0.0265
32.9° C	±0.05° C	11.3370	±0.0542
37.7° C	±0.19° C	22.2370	±0.4244

The following numerical relationship exists between the inversion constants K and the corresponding constant temperatures:

$$\log K = B + aT + bT^2 \qquad \text{Eq. 4}$$

a, b and B are numberical constants.

*The mean error of the mean value is calculated according to the expression:

$$\sqrt{\frac{\Sigma \Delta^2}{n(n-1)}}$$

Substituted in Equation 4, they give:

$$\log K = -1.24552 + 0.07853T - 0.0002585T^2 \qquad \text{Eq. 5}$$

This equation is presented graphically in Figure 1. The agreement between observed and computed values is excellent.

b) What does the concept of "effective mean temperature eT " signify?

As temperature rises, the inversion rates, and with them the accompany- inversion constants K, increase rapidly. The temperature quotient of these constants amounts to 3.8 -5 9 for each 10° temperature difference. When the inversion takes place in a sugar solution, whose temperature is not held constant but allowed to vary in the course of the observation, the periods of higher ambient temperature have significantly greater effect on the overall inversion effect for the total period than do those of lower temperature. The observed total amount of inversion for the investigation period (quantity of invert sugar formed) corresponds to an "effective mean temperature" which must be higher than the arithmetic mean of the temperature variations. The effective mean temperature, designated as eT , does not correspond to the arithmetic temperature mean of an observation period, but rather to an exponential mean.

Not only cane sugar inversion, but all other chemical and biochemical reactions occur more rapidly at higher temperatures than at low ones (RGT-Law of Van't Hoff, 1884). When a reaction takes place predominantly in one direction during a period involving various temperature levels, the given reaction effect R at the end of the period exhibits a stronger influence from the higher temperature levels than from the lower.

The exponential mean temperature eT measured with help of the sugar inversion departs the wider from the arithmetic mean, the greater was the

temperature variations during the observation period. The departures are always positive.

Individual Temp Levels (over 14 days)	Arithmetic Mean of Temp Levels	Experimental eT-Mean	Difference
18.4° C 18.4° C	18.4° C	18.4° C	0.0° C
18.4° C 24.2° C	21.3° C	21.9° C	+0.6° C
24.2° C 34.2° C	29.2° C	30.8° C	+1.6° C
3.6° C 34.1° C	18.8° C	29.3° C	+10.5° C

Were this reaction to take place in a constant temperature milieu rather than in a variable temperature one, this constant temperature would have to be higher than the arithmetic mean of the variable temperature system in order to achieve the same reaction quantity R. This constant temperature would then correspond to the effective mean temperature over the entire observation period; the eT-quantity is a measure of this.

This dependency of the reaction constants on the temperature is given in Tables 2 and 3.

Table 2

The Ion Products in Water Important to Hydrolysis Increase Very Rapidly with Increasing Temperature.

Temperature	Ion Products (H) (OH) K_W	Relative Value for K_W	Temperature Quotient/10° C
0° C	$0.08 \cdot 10^{-14}$	1.0	
			4.2
18° C	$0.61 \cdot 10^{-14}$	7.6	
			2.3
25° C	$1.00 \cdot 10^{-14}$	12.5	
			2.3
34° C	$2.10 \cdot 10^{-14}$	26.2	
			1.6
50° C	$5.4 \cdot 10^{-14}$	67.5	

Table 3

Temperature Quotients of Certain Enzyme Reactions

System	Temperature Range	Temperature Quotient
Casein destruction by trypsin	21-39° C	5.30-3.30
Protein destruction by trypsin	19-30° C	3.75-1.88
Olive oil dissociation by pancreatic juice	0-26° C	2.02
Olive oil dissociation by castor oil lipase	15-35° C	2.66-1.20
Maltose dissociation by yeast maltase	10-40° C	1.90-1.28
Glucose fermentation by yeast	15-25° C	2.8

These quotients are in part of the same order of magnitude as those for cane sugar inversion and thus also for the measuring system selected for investigation of the effective mean temperature.

c) Hints on Methods

1. Chemicals required for preparation of the buffered sugar solution,

The preparation of the measuring solution is discussed in an earlier published work. (4) The chemicals must be in chemically pure form. The crystallized cane sugar occasionally contains a slightly acid contaminant. It therefore is necessary to test the cane sugar solution prior to heat sterilization to determine whether the pH-value of the solution lies above 6.5. If it is appreciably less than this figure, unwanted inversion during the sterilization is unavoidable. When an "acid" sugar solution occurs, it can be sufficiently neutralized with a few drops of $Ca(OH)_2$. The pH-value is then once more tested to see if the desired value around 7 has been reached. Experience has shown pure cane sugar as obtained from a grocery store is satisfactory.

2. Concentration of the cane sugar solution.

A concentration of around 50% cane sugar in the sealed ampoule is advantageous. The initial rotation angle is then around +25°. A terminal

rotation angle $\beta_0 = -9^{\circ}$ encompasses a sufficiently wide range of angles. The constants given above are valid for sugar concentrations between 40% and 60%. They can be altered at higher sugar concentrations, as one of us earlier was able to show. (5)

3. Choice of pH-value for the buffered sugar solution.

Inversion rate of the buffered sugar solution is altered with the hydrogen ion concentration according to Equation 1:

$$\frac{dx}{dt} = K \cdot H \cdot (A - x)$$

When eT-measurements (in a given locality) are planned for short periods and low temperatures are expected, the inversion rate can be increased by raising the hydrogen ion concentration. When longer research periods are planned with expectation of higher temperatures, the inversion rate can be diminished by reduction of the ion concentration. In subalpine and alpine zones, pH-values between 2.5 and 3.0 are very satisfactory on the cooler north slopes as well as for measurements on south exposures; the research period can last from a few weeks to several months.

<u>It is essential that the hydrogen ion concentration of the buffered sugar solution be known exactly</u>. It must be determined as accurately as possible prior to setting out the ampoules in the field, and entered in Equation 3 for calculation of the inversion constants.

The hydrogen ion concentration does not change within the sterile ampoules. Even after year-long research periods, no change in pH can be detected in ampoules left in the field.

(end of translated section)

The authors go on to describe use of the sugar solution ampoules in the field and various factors affecting them. The significant points in this part

of their paper are summarized as follows:

1. About 15 cc of solution in a 20 cc ampoule provides ample quantity for convenient field use and easy test in the laboratory.

2 Use of colored glass in the ampoules results in a slightly higher eT-value, due to absorption of solar radiation by the glass when the ampoules are exposed in the air without shade protection. The use of clear glass is recommended.

3. Tests showed that the sugar inversion in the ampoules is unaffected by ultraviolet radiation.

4. The ampoules must be transported from laboratory to the field as quickly as possible and kept cooled until actually installed. Chilling in a refrigerator and transport in an insulated case is recommended. Where an extended length of time will occur between preparation and installation in the field, a polarimeter should be provided in the field so that the rotation angle can be established immediately prior to installation.

5 The ampoules are suspended from a string or wire when air temperatures are being measured, and may be provided with a radiation shield. (See illustrations in Reference 1). For measurement of soil temperatures, a small pit is excavated, the ampoules inserted in holes in the pit wall and the pit refilled.

6. Accuracy of the temperature measurement is high. Identically exposed ampoules yield eT-values agreeing with o.1^{o} C.

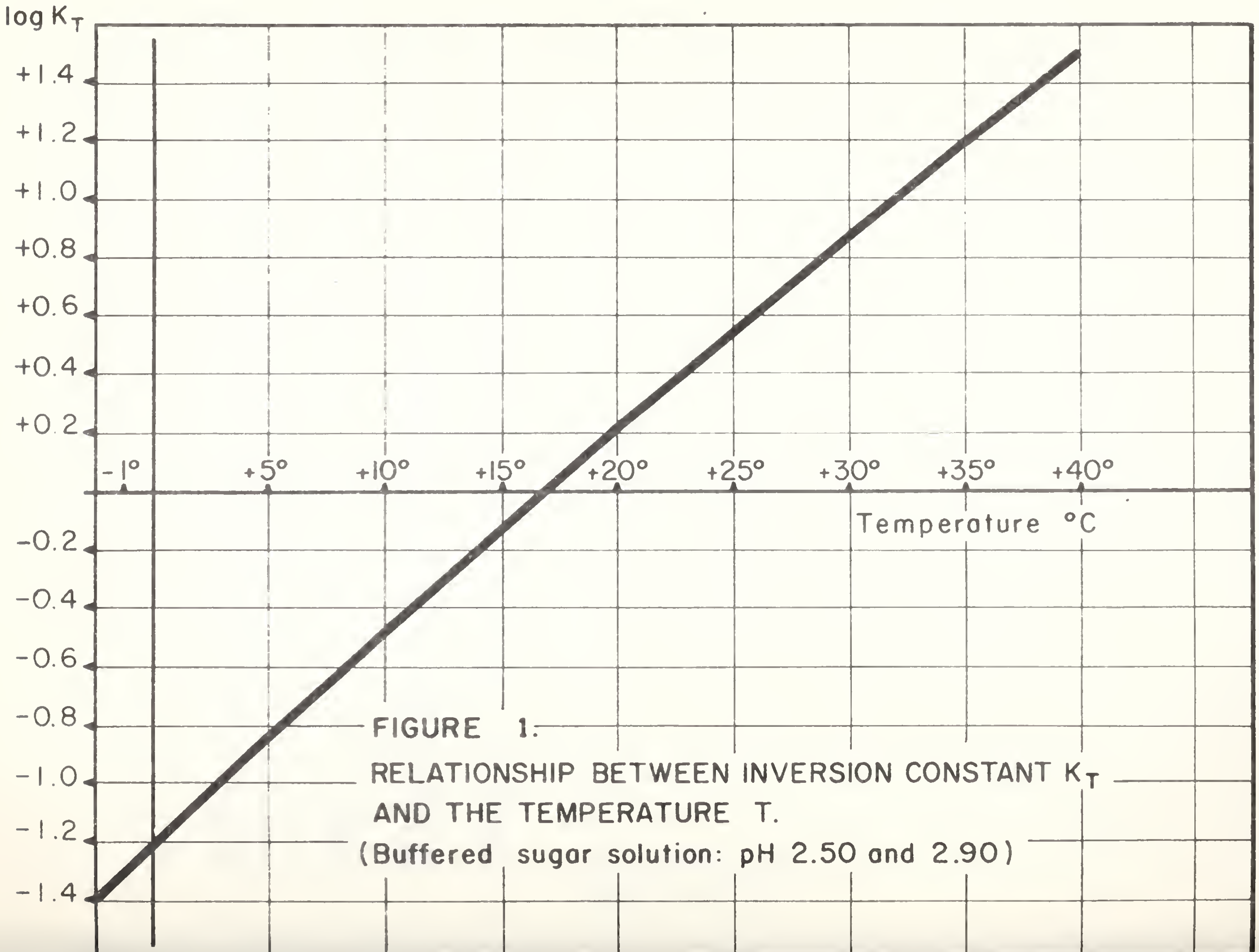

FIGURE 1.

RELATIONSHIP BETWEEN INVERSION CONSTANT K_T AND THE TEMPERATURE T.

(Buffered sugar solution: pH 2.50 and 2.90)

References Cited

1. LaChapelle, E. An Inspection Trip to Europe. U.S.F.S. Internal Report, Ogden, Utah, January 1961

2. Pallman, H. and E. Frei Beitrag zur Kenntnis der Lokalklimate einiger Kennzeichender Waldgesellschaften des Schweizerischen Nationalparkes. Ergebnisse der wissenschaftlichen Untersuchungen des schweizerischen Nationalparkes, Band 1 (Neue Folge), Heft 10, 1943 .

3. Tamm, E. (Title not given) Landw. Jahrbucher, Bd 83, 1936 (pp 457-554) Bd. 88, 1939 (pp 479-548).

4. Pallman, H., E. Eichenberger and A. Hasler. (Title not given) Ber. Schweiz. bot Ges.: 50, 1940 (pp 337-362).

5. Pallman, H. (Title not given) Kolloid-Beihefte. 30, 1930 (p. 369 ff.)